66-920747-10
EGG-M-92305

EGG-M--92305

DE92 018013

AIAA-92-3271

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Re-entering the Biosphere**

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**AIAA/SAE/ASME/ASEE
28th Joint Propulsion
Conference and Exhibit
July 6-8, 1992 / Nashville, TN**

MASTER

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Systems To Prevent Nuclear Material From Re-entering the Biosphere

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Abstract

Nuclear systems are key to the success of many space missions as we have witness in the Apollo science packages, Viking Mars landers, and Pioneer and Voyager planetary exploration missions. There is always a concern that nuclear materials will re-enter the biosphere from a mission abort. In fact, this has happened for radioisotope and reactor power systems. Until now, the emphasis has been on incorporating on-board means to protect the biosphere. With possible increased use of nuclear power and propulsion systems in space, Project SIREN (Search, Intercept, Retrieve, Expulsion, Nuclear) has determined that external means can be used as a back up to current on-board systems to provide assured prevention of nuclear materials from re-entry once in space. The technology base to implement a SIREN vehicle has been assessed and a data base and mission analysis program prepared (called THOR) to evaluate various missions. The degree of hazard from existing nuclear power systems in space has been assessed and found to be significant.

Introduction

Project SIREN (Search, Intercept, Retrieve, Expulsion, Nuclear) is evaluating the mission requirements, technologies, and operational strategies needed to rendezvous with and capture aerospace radioactive materials (e.g. a distressed or spent space reactor core) before such materials can reenter the terrestrial atmosphere and then to safely move these captured materials to an acceptable space destination for proper disposal. This use of systems external to a satellite allows many opportunities for success in preventing the nuclear materials from re-enter into the atmosphere. It also is investigating means to prevent the break-up of nuclear powered systems already in space. These number approximately 40

counting the USSR RORSAT satellites and U.S. SNAP-10A, Transit and Nimbus satellites. SIREN is like having a fire station, it prepares for a possible problem before it might occur, hoping it will never be needed.

Nuclear powered systems have been used by the U.S. and USSR in many successful missions (Tables 1 and 2). Systems in Table 1 have successfully powered the Apollo science packages, Viking Mars landers, Pioneer and Voyager planetary exploration missions as well as defense satellites. However, a number of missions have been aborted, not from a failure originating within the nuclear power subsystem. A list of nuclear powered systems that have re-entered the biosphere is given in Table 3. All of these missions have incorporated on-board means to protect the biosphere. However, with the need for increased use of higher powered systems in space for both civilian and defense missions, and increased awareness of the need to protect the environment, efforts are underway to determine what means can be used to assure that nuclear materials do not re-enter the biosphere.

Recent national studies support the need for nuclear power for lunar bases and Mars expeditions and surface bases, interplanetary transportation systems, deep Solar System exploration missions, and large-scale Earth-orbiting civilian platforms and defense missions. When used at sufficiently high orbits, the radioactive fission products created in the operation of such space nuclear reactors can decay by natural processes to insignificant, harmless levels prior to any atmospheric re-entry of the aerospace system centuries or millennia later. However, there are other important

<u>Power Source</u>	<u>Spacecraft</u>	<u>Mission Type</u>	<u>Launch Date</u>	<u>Status</u>
SNAP-3B7	TRANSMIT 4A	Navigational	29 June 1961	RTG operated for 15 years. Satellite now shutdown but operational.
SNAP-3B8	TRANSIT 4B	Navigational	15 November 1961	RTG operated for 9 years. Satellite operation was intermittent after 1962 high-altitude nuclear test. Last reported signal in 1971.
SNAP-9A	TRANSIT 5-BN-1	Navigational	28 September 1963	RTG operated as planned. Non-RTG electrical problems on satellite caused satellite to fail after 9 months.
SNAP-9A	TRANSIT 5-BN-2	Navigational	5 December 1963	RTG operated for over 6 years. Satellite lost navigational capability after 1.5 years.
SNAP-9A	TRANSIT 5-BN-3	Navigational	21 April 1964	RTG operated as planned. Mission was aborted because of launch vehicle failure.
SNAP-10A (Reactor)	Snapshot	Experimental	3 April 1965	Reactor operated successfully as planned. Satellite shutdown reactor after 43 days.
SNAP-19B2	Nimbus-B-1	Meteorological	18 May 1968	RTGs operated as planned. Mission was aborted because of range safety destruct. RTGs recovered.
SNAP-19B3	Nimbus III	Meteorological	14 April 1969	RTGs operated for over 2.5 years (no data taken after that).
SNAP-27	Apollo 12	Lunar	14 November 1969	RTG operated for above 8 years (until station was shutdown).
SNAP-27	Apollo 13	Lunar	11 April 1970	Mission aborted on way to moon. Heat source returned to South Pacific Ocean.
SNAP-27	Apollo 14	Lunar	31 January 1971	RTG operated for about 6.5 years (until station was shutdown).
SNAP-27	Apollo 15	Lunar	26 July 1971	RTG operated for over 6 years (until station was shutdown).
SNAP-19	Pioneer 10	Planetary	2 March 1972	RTGs still operating. Spacecraft successfully operated to Jupiter and is now beyond orbit of Pluto.
SNAP-27	Apollo 16	Lunar	16 April 1972	RTG operated for about 5.5 years (until station was shutdown).
Transit-RTG	"TRANSIT" (TRIAD-01-1X)	Navigational	2 September 1972	RTG still operating.
SNAP-27	Apollo 17	Lunar	7 December 1972	RTG operated for almost 5 years (until station was shutdown).
SNAP-19	Pioneer II	Planetary	5 April 1973	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.
SNAP-19	Viking I	Mars	20 August 1975	RTGs operated for over 6 years (until lander was shutdown).
SNAP-10	Viking 2	Mars	9 September 1975	RTGs operated for over 4 years until relay link was lost.
MHW-RTG	LES 8	Communications	14 March 1976	RTGs still operating.
MHW-RTG	LES 9	Communications	14 March 1976	RTGs still operating.
MHW-RTG	Voyager 2	Planetary	20 August 1977	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, and beyond.
MHW-RTG	Voyager 1	Planetary	5 September 1977	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn and beyond.
GPHS-RTG	Galileo	Planetary	18 October 1989	RTG still operating. Spacecraft.
GPHS-RTG	Ulysses	Planetary	6 October 1990	RTG still operating. Spacecraft.

Table 1 Summary of Space Nuclear Power Systems Launched by U.S.

Satellite Designation	Launch Date	Termination Date
Cosmos 367	October 3, 1970	October 3, 1970
Cosmos 402	April 1, 1971	April 1, 1971
Cosmos 465	December 25, 1971	January 3, 1972
Cosmos 516	August 21, 1972	September 22, 1972
Cosmos 626	December 27, 1973	February 9, 1974
Cosmos 651	May 15, 1974	July 25, 1974
Cosmos 654	May 17, 1974	July 30, 1974
Cosmos 723	April 2, 1975	May 15, 1975
Cosmos 724	April 7, 1975	June 11, 1975
Cosmos 785	December 12, 1975	December 12, 1975
Cosmos 860	October 17, 1976	November 10, 1976
Cosmos 861	October 21, 1976	December 20, 1976
Cosmos 952	September 16, 1977	October 7, 1977
Cosmos 954	September 18, 1977	October 31, 1977
Cosmos 1176	April 29, 1980	September 10, 1980
Cosmos 1249	March 5, 1981	June 18, 1981
Cosmos 1266	April 21, 1981	April 28, 1981
Cosmos 1299	August 24, 1981	September 5, 1981
Cosmos 1365	May 14, 1982	September 26, 1982
Cosmos 1372	June 1, 1982	August 10, 1982
Cosmos 1402	August 30, 1982	December 28, 1982
Cosmos 1412	October 2, 1982	November 10, 1982
Cosmos 1579	June 29, 1984	September 26, 1984
Cosmos 1607	October 31, 1984	February 1, 1985
Cosmos 1670	August 1, 1985	October 22, 1985
Cosmos 1677	August 23, 1985	October 23, 1985
Cosmos 1736	March 21, 1986	June 21, 1986
Cosmos 1771	August 20, 1986	October 15, 1986
Cosmos 1818*	February 1, 1987	July, 1987
Cosmos 1860	June 18, 1987	July 28, 1987
Cosmos 1867*	July 10, 1987	July, 1988
Cosmos 1900	December 12, 1987	April 14, 1987
Cosmos 1932	March 14, 1988	May 19, 1988

*Topaz

Table 2 Soviet Orbital Reactors Program History

REENTRIES OF NUCLEAR POWER SOURCES

- Transit 5BN-3 (SNAP 9A generator), 1964
- Nimbus B-1 (SNAP 19 generator), 1968
- RORSAT(?) (nuclear reactor), 1969
- Cosmos 300 and 305 (Po-210 Lunokhod generators), 1969
- Apollo 13 (SNAP 27 generator), 1970
- Cosmos 954 (nuclear reactor), 1978
- Cosmos 1402 (nuclear reactor), 1983
- Cosmos 1900 (nuclear reactor), 1988 (core boosted from 120 km)

Table 3

space missions that will require the start of reactor operations while the aerospace system is still at orbits lower than those considered sufficiently high to accommodate fission product decay. In the past, a chemical booster has been incorporated into these lower altitude satellites. Unfortunately, as shown by operational experience (i.e., COSMOS 954 and 1402), these booster mechanisms can fail. Furthermore, it may not always be desirable to incur the mass-penalty associated with an on-board booster system. Project SIREN is, subsequently, being investigated as an external, independent means to capture and expel spent or distressed aerospace nuclear sources under these circumstances and similar situations that could arise with the expanded use of nuclear power systems in space in the next century.

Elements of a SIREN Mission

The elements of a SIREN mission are presented in Figure 1. These include: (1) tracking facilities to locate the satellite with nuclear materials aboard, (2) maneuverable SIREN vehicle, (3) means to capture the target satellite, (4) means to separate the nuclear materials from the remainder of the satellite, (5) disposal mechanisms, (6) means to disengage and recover the SIREN vehicle, and (7) means to assess success. The tracking system can take advantage of the Space Surveillance Network consisting of a network of both radar and optical sensors. The radars are used for detection and tracking of objects in both low-earth orbit and geosynchronous

orbit. The optical systems such, as the Air Force Maui Optical Station facility located on the island of Maui, Hawaii, can be used for detection and tracking of objects in high Earth orbit as well as to determine rough physical characteristics of objects in space (see Figure 2).

A conceptual design of a SIREN vehicle is given in Figure 3. It includes propulsion for intercepting the target satellite, maneuvering in the vicinity of the satellite, and recovering the SIREN vehicle. A number of sensors are mounted on the satellite for inspection and operation of teleoperated devices. Also illustrated is a mechanism for capturing the target satellite. It is assumed that the satellite to be captured is spinning; capture means must take into account that the target satellite is non-cooperative and radioactive. Also, the SIREN vehicle incorporates teleoperated devices for detaching the nuclear materials. This detachment is to reduce the mass of the disposal material. Disposal rockets then must be attached to the nuclear materials for disposal to higher orbit or other locations away from earth. Support systems, such as command and control, power supplies, communications, etc. are also on the SIREN vehicle.

The system is designed to recover the SIREN vehicle. Whether it should be ground- or space-based depends on the space infrastructure in existence at the time and the inclinations of the target satellites of interest. A major consideration in the formulation of the SIREN system is the ability to repeat the operations if not completely successful. If there is a failure to successfully dispose of the nuclear materials, this external arrangement allows for multiple tries until success is achieved.

SIREN Data Base

To assess the use of available or projected technologies needed to perform a SIREN mission and the need for additional technology developments, a data base and mission analysis program has been developed. This program, called THOR for Technology Hierarchy for Orbital Recovery, is now operational, though the initial quantity of technology data incorporated is limited. It is a

Figure 1 SIREN Goal Tree

fully interactive, technology model data base and mission analysis code to identify technologies and missions requirements for candidate SIREN rescues. It incorporates innovative and efficient means for performing a range of trade studies for different reactor operating conditions and orbital scenarios. Technologies in the data base include: tracking facilities, capture and transfer vehicles, robotics, disposal options and reactor descriptions. Mission analysis scenarios can be investigated to cover tracking, capture, and disposal. Technology readiness level information is used to assess the availability of a given technology to perform missions on given desired event dates. Trade studies can be performed for a variety of scenarios and parameter spaces defined.

The THOR user defines the mission scenario for the trade studies. This consists of choosing the event date for the mission, the level of technology that the user is willing to accept for this mission and the aspects of the mission in which the user is interested. If sufficient technology is not available or if one wants to test the effects of new technology, a "hypothetical" technology can be added to the data base. For a given mission, THOR might investigate 10 different capture vehicles, 6 transfer vehicles, 8 launch

vehicles and 2 launch facilities for a given nuclear powered satellite. If all of these technologies could meet the mission needs, over 3,500,000 combinations would be considered by THOR before arriving at a mission design. If only half of the technologies would meet the mission criteria, the combination is still 32,000. By computerizing this process with the methods used in THOR, endless tradeoffs can be made very quickly (minutes) and accurately.

THOR is programmed for use on a 286-, 386-, or 486 PC computer running with Microsoft Windows 3.0. A mouse or compatible pointing device is used for selection of parameters. At least 2 MB RAM and a math co-processor is used.

THOR Analysis

To perform an analysis of a mission, such as the inspection and boost of the Transit (TRIAD-01-0X) satellite launched in 1972 with an apogee of 838 km and perigee of 742 km (projected orbital life of 150 years), one would first insert into the data base a description of the power system and payload. Currently, the data base includes descriptions of SNAP-10A, Topaz II, and SP-100. The data to be inserted includes: the

Figure 2 Space Surveillance Network (SSN) and Field of View at 500 km

technology readiness, dates for technology level of interest, references, number of components, mass, volume, g-load limits, dimensions, moment of inertia, reluctance, radar signature, power level, neutron and gamma fluxes, radiator temperature, mass and volume, communications and manufacturer. The standard payload description is for a communication satellite. Information on the particular satellite of interest can be entered. THOR has various tracking assets at the AMOS facility in Hawaii. The program will compute the ability of the tracking facility to locate the Transit satellite and tell you how often it can be viewed. For a capture and boost mission, THOR will than compute the launch vehicles that can be used either out of Canvenal or Vandenberg launch facilities. Currently, the program incorporates the Space Shuttle, Titan II and IV launch vehicles and Centaur, IUS, PAM IID, TOS and Transtage transfer vehicles. For capture, THOR currently includes a description of the OMV. Various orbital disposal options are included from higher Earth orbits, geosynchronous and five times geosynchronous, to circular solar orbit, solar elliptical and solar impact, and lunar orbit or surface. Technology status are projected for each part of the mission. The result will be a description of options that can boost the Transit satellite to the new disposal location based on the technology capabilities and date the mission is desired. If no options are available, one can inserted projected technologies to identify what is needed to perform the mission. Or, one can evaluate the different launch vehicle requirements based on the disposal mode.

Debris Analysis of Nuclear Systems

Currently, there are over forty satellites that have nuclear materials on-board in low Earth orbits. Even if no additional nuclear powered

Figure 3 SIREN

satellites are launched, one must be concerned with any events that might affect these satellites. For instance, could a nuclear debris belt be formed by the collision of debris or meteoroids with these satellites.

To analyze this problem, the orbits of 36 Russian nuclear powered satellites was obtained from the Committee on the Peaceful Uses of Outer Space report to the United Nations General Assembly (90-04895). The orbital data was input to a ephemeris code, which is a variant of the program used in the THOR, and the number of close approaches were computed. The results are statistical in nature. The analysis showed that a nuclear powered satellite unit will likely suffer damage impact (i.e., -1 cm object-size collision) within 10 years, penetrating impact (i.e., between 5 and 10 cm collision) within the next 25 to 35 years and a catastrophic impact (i.e., -50 cm diameter collision) 5 to 8 years later. This will occur within the region from 900-1000 km. These projections agree very closely with recent Soviet predictions.²

Other Applications

SIREN can support a wide range of missions in low Earth Orbit that are of common interest to the Department of Defense, National Aeronautics and Space Administration and Department of Energy (see Figure 4). So far, we have been discussing SIREN's primary mission of preventing radioactive materials from re-entry into the biosphere. In the previous section, we discussed the possibility of nuclear debris belts being formed if no remedial actions are taken. The SIREN vehicle presents an option to take remedial actions. Since 1978, the United Nations has been developing a consensus on the use of nuclear power in Earth orbit. SIREN can offer an external means to protect the Earth's environment against re-entering radioactive materials. It can form the basis for international cooperation in this field in place of the adversant attitude that now exists. And, SIREN can enhanced public awareness and acceptance concerning the use of nuclear systems in space.

Satellite servicing and maintenance will eventually become a major activity in space. The same systems needed for a successful SIREN project can provide valuable orbital functions experience in support of this function.

For NASA, SIREN can directly support the space exploration plans for exploration

Figure 4 Supports Wide Range of Missions

of the moon and Mars by providing for safety against a mission abort at the initiation of the mission. It makes it possible to safely start the mission from lower Earth orbits. As seen in Figure 5, this is important in reducing the cost of these missions. If an abort does occur, SIREN can be used as a repair vehicle. Also, planetary science missions, that might use nuclear electric or nuclear thermal propulsion, can use SIREN as a safety system.

Defense missions can take advantage of SIREN by providing a retrieval and servicing capable for satellites in low orbits. It also provides a back-up safety system for nuclear orbit transfer vehicles and satellites that incorporated nuclear power plants.

The Department of Energy, with its responsibility for safety, can use SIREN as a means to enhance safety of systems that use nuclear power plants in low Earth orbit.

Summary

The SIREN Program is important because: (1) it demonstrates the awareness to public concerns on space use of nuclear power and propulsion systems and the potential of nuclear materials re-entering the biosphere and that precautionary actions are being

Figure 5 Mars Payload Performance vs. Orbit Height

taken to protect the biosphere; (2) it provides a mechanism for active public involvement in space nuclear safety; (3) it provides a means for international cooperation since the problem is international in scope both from launcher states and potential landing sites; (4) it is timely to establish international guidelines for space nuclear systems; and (5) SIREN supports many emerging space activities, such as space debris remediation, servicing and maintenance in space, and such initiatives as strategic defense and space exploration. The findings of the SIREN program are:

- fundamental technology ideas exist, but component development and an integrated systems (hardware, organization, etc.) are needed;
- permanent disposal options are available for spent nuclear systems with existing or planned transfer vehicles;
- "rescuing" nuclear power systems of other than country of origin requires new thinking in the space law community, new international agreements, and complex coordination by many inter-national organizations and national authorities;
- unique, comprehensive component data base and mission analysis program (THOR) developed (this is a valuable tool for all space servicing and maintenance programs);

- for nuclear power systems already in space, cata-strophic collisions of >10 cm will happen within 30-40 years with systems located in the 800-1000 km belt; and
- SIREN vehicle excellent for many non-nuclear activities such as debris remediation, servicing, maintenance, and satellite retrieval.

Acknowledgement

This work was sponsored by the Strategic Defense Initiative Organization under contract with the Idaho National Engineering Laboratory, Program Number N0626 under DOE Idaho Field Office Contract No. DE-AC07-76ID01570.

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